KFKI-74-8

K. TOMPA

NMR IN DILUTE ALLOYS

Hungarian Academy of Sciences

CENTRAL
RESEARCH
INSTITUTE FOR
PHYSICS

BUDAPEST

KFKI-74-8

NMR IN DILUTE ALLOYS

K.Tompa

Central Research Institute for Physics, Budapest, Hungary
Solid State Physics Department

The manuscript of this preprint was prepared for a talk at the meeting of International Society of Magnetic Resonance, Bombay, India, 1974 January and will be published in Journal of Pure and Applied Chemistry

SUMMARY

The experimental results concerning the electric field gradient and the local magnetic field around substitutional impurities in Cu based dilute alloys were summarized. Comparing the experimental data with theoretical models we came to the conclusion, that only the first order quadrupole wipe-out number characteristic of the asymptotic charge density oscillation around the impurities can presently be properly interpreted.

ÖSSZEFOGLALÁS

Összegyüjtöttük Cu alapu hig ötvözetekben a szubsztituciós szennyezések körüli elektromos térgradiensre és lokális mágneses térre vonatkozó kisérleti eredményeket. Elméleti modellekkel való összehasonlitás alapján arra a következtetésre jutottunk, hogy jelenleg elfogadható módon csak az idegen atom körüli aszimptotikus töltéssürüség oszcillációra jellemző elsőrendü kvadrupol kiszórási szám értelmezhető.

РЕЗЮМЕ

Собраны экспериментальные результаты, связанные с измерением градиента электрического поля и внутреннего магнитного поля вокруг замещающих примесей в разбавленных сплавах на основе Cu . Из результатов сравнения с теоретическим моделями сделан вывод, что удовлетворительно интерпретируется лишь число уничтожения квадрупольного эффекта первого порядка, характеризующее асимптотическую осцилляцию плотности заряда вокруг инородного атома.

I. INTRODUCTION

In the last 10 or 15 years the study of dilute alloys contributed substantially to our knowledge of metals and alloys. Nevertheless, there are still many problems which require further experimental and theoretical investigations.

The study of microscopic /local/ behaviour is expected to furnish new data in addition to the transport, thermal and magnetic properties. The most effective tool for the study of local properties is known to be the NMR spectroscopy.

It is beyond the scope of this paper to review all the results achieved by NMR spectroscopy. The present considerations will be restricted to the electric field gradient and the local magnetic field perturbations in the environment of the alloyant atoms /impurities/ in a copper matrix. This report has been written with three objectives. First we want to summarize the latest experimental results in this field, second, the results obtained in our laboratory will be presented alongside with those of other authors. Finally, the interpretation of the experimental data will be discussed in detail, however, without an attempt at the confirmation of any given theory. The alloys of Cu with 3d transition metals will be specifically considered. The physical properties and the anomalies observed on these alloys have been dealt with in a large number of papers. As reference, three articles of a monographical character can be mentioned [1, 2, 3].

II. REVIEW OF EXPERIMENTAL DATA

Before actually surveying the experimental results, it seems of interest to consider briefly the type of samples used for the experiments, their preparation and some consequences of the alloying techniques applied.

S a m p l e s . NMR measurements are usually made on powder samples, lately, also monocrystals have been applied for the study of dilute alloys [4, 5]. The samples introduced in Budapest differ from the conventional powder samples. Here about 15 μ thick foils are sandwiched with insulating layers [6].

With these sandwich type samples the accuracy of the relative amplitude measurement of the NMR spectrum is found to be around ± 1% [7], thus better than that reported for powder samples. It has to be noted that the accuracy of the amplitude, i.e. intensity measurement, is of essential importance in the evaluation of the quadrupole effect.

P r e p a r a t i o n o f s a m p l e s. Two non-trivial problems are worth mentioning in connection with the alloying procedure. One of them is fast cooling down, the other the internal oxidation.

Fast cooling is applied in order to maintain the impurity concentration in the solution. In this case the vacancies frozen along with the impurities may considerably effect the result of the measurement [8].

Oxidation can occur at high temperatures when the samples happen to be under an atmosphere containing oxygen /e.g. poor vacuum with pressures from 10^{-5} to 10^{-4} mmHg, technical grade argon, etc./ This has been observed in the early experiments on dilute Cu-Ga alloys [9]. Depending on the annealing time, practically any experimental value can be obtained in poor vacuum e.g. even the first order quadrupole effect wipe-out number of $n_1=0$ which holds for the unperturbed case /pure metal/. It is known that many alloyants have a tendency to oxidation in Cu matrix [10]. Thus, it is not the number of the first order quadrupole effect wipe-out number that decreases, but the number of "active" Ga impurities can be reduced even to zero.

E x p e r i m e n t a l m e t h o d s. Various experimental setups have been used in the measurements referred to, such as the most simple continuously excited "broad line" spectrometers, the field cycling method introduced by Redfield [11] and the SEDOR /spin-echo double resonance/ technique [12]. It is of interest to note that the most simple technique essentially contributed to the better understanding of the problems.

1. FIELD GRADIENT MEASUREMENTS

The literature on the quadrupole effect in the NMR spectrum has been reviewed in [13]. The quadrupole effect in dilute alloys has been discussed in the theoretical papers by Friedel and Blandin [14] and by Kohn and Vosko [15]. There are two important experimental papers to be referred to [16] and [7], Some results of the theoretical approaches will be discussed in the next chapter.

The electric field gradient measurements can be divided into three groups, as illustrated in Fig.1.

Thus the measured values can reflect the field gradient at the nuclei on given coordination shells or the average value of the field gradient in the range close to the impurities and that in the asymptotic range. The latter two

are characterized by the second and first order quadrupole effect wipe-out numbers n_2 and n_1, respectively.

Table I lists the parameter values of the field gradients measured at nuclei on the given coordination shells in dilute Cu-based alloys.

Table II shows the wipe-out numbers characteristic of the first and second order quadrupole perturbations in Cu-based alloys.

On inspection, no comparable trends can be noticed on the data of Tables I and II. The values of n_1 and n_2 in Table II show several similar tendencies.

2. LOCAL MAGNETIC FIELD MEASUREMENTS

The listing of the data obtained from the measurement of the local magnetic field in the environment of impurity atoms will be restricted to the values of the magnetic field measured at nuclei on the coordination shells at given distance from the impurity atom. The discussion will not be extended to the study started by Owen et al. [23] continued by Behringer, Vander Lugt et al. and Sugawara [24] which concerned mainly the broadening and the shift of the NMR spectrum. The coupling constant J_{sd} determined from these investigations. The anomaly of the NMR spectrum at about the Kondo temperature [25] will be also left out of consideration since no local magnetic field measurement has been reported on the same metal in both the non-magnetic and the magnetic state.
The results of the local magnetic field measurements are listed in Table III.

III. INTERPRETATION OF THE EXPERIMENTAL RESULTS

1. THEORIES

The theoretical relations needed for the interpretation of the experimental data are briefly referred to. According to the generally accepted definition [26] the field gradient can be attributed to two contributions, one of them is called "size effect" which is due to the lattice deformation caused by the impurity, the other is called "charge effect" caused by the conduction electron density perturbation around the impurity.

L a t t i c e d e f o r m a t i o n a r o u n d i m p u r i t i e s - s i z e e f f e c t s. The contribution from lattice deformation appears first in terms of the continuum model of solids as the Blatt correction |27|.

$$\Delta Z' = \Delta Z - \frac{3}{\gamma E} \cdot \frac{1}{a} \frac{da}{dc} Z_o \qquad /1/$$

where ΔZ is the matrix impurity valence difference, $\gamma_E = 3(1-\sigma)/(1+\sigma)$, σ is the Poisson ratio, $\frac{1}{a}\frac{da}{dc}$ the relative change in the lattice constant per impurity concentration, Z_o is the charge of matrix ions.

The contribution from the lattice deformation to the electric field gradient is given by Sagalyn et al. [26] as

$$q_\lambda = \lambda \frac{27}{2^{3/2}\pi\gamma E} \cdot \frac{1}{a}\frac{da}{dc} \; r^{-3} \qquad /2/$$

where r is the distance from the impurity and λ is an empirical parameter. The meaning of λ was discussed more fully in an earlier report [28] and in our direct measurement it was found that $\lambda < 1.5$, which is only one tenth of the contribution to the field gradient determined by Sagalyn et al. and thus about 10 per cent of the contribution from Friedel oscillation. However this estimation does not permit any inferences to be made on the effect of lattice deformation in the neighbourhood of the impurities.

The theory of Beal-Monod and Kohn [29] has to be mentioned as a comprenensive theory of lattice deformation which accounts for both the Blatt and Sagalyn effects, and also determines the validity of the Blatt correction. However, practically one can not use the prediction of this theory in the evaluation. The Blatt correction is the only term that we can use from the "size" effect formulation.

Electric field gradient due to charge density oscillation around impurity. According to Kohn-Vosko's [15] and Blandin-Friedel's [14] asymptotic theory, the Z component of the electric field gradient at the matrix nuclei around the impurity in metals of cubic symmetry can be expressed in the form

$$q = \frac{8\pi}{3} \alpha \, \Delta n/r/ \qquad /3/$$

where α is the enhancement factor accounting for both the Bloch character of the conduction electrons and the Steinheimer antishielding factor [29], predicted for Cu as 25.5 [15], up to this time we have this predicted value for α and an estimation of the upper limit of α [28] as $\alpha<25$. The electric field gradient is directly related to the charge density oscillation $\Delta n/r/$, and

$$\Delta n/r/ = \frac{A}{r^3} \cos\,(2k_F r + \;)$$

$$A \sin\varphi = \frac{1}{2\pi^2} \sum_\ell (-1)^\ell \, (2\ell+1) \, \sin^2\eta_\ell \qquad /4/$$

$$A \cos\varphi = \frac{1}{2\pi^2} \sum_\ell (-1)^\ell \, (2\ell+1) \, \sin\eta_\ell \; \cos\eta_\ell$$

where k_F is the Fermi wave number, and η_ℓ stands for the phase shifts of the scattered partial wave characterized by the quantum number ℓ at the Fermi energy. The phase shifts satisfy the Friedel sum rule

$$Z = \frac{2}{\pi} \sum_{\ell} (2\ell+1)\eta_\ell \qquad /5/$$

which is the condition of self-consistance for the scattering potential. The methods used for the evaluation of phase shifts are summarized in [7].

For transition metal impurities the Friedel - Anderson theory [14], [30] leads to the same expression as given above /4/ provided that the distance between the Fermi level and the virtual level is great and that the screening charge contains contributions from states of different symmetries. If the virtual level is close to the Fermi level, resonance scattering i.e. the term $\ell = 2$ becomes dominant, and in accordance with the Friedel sum rule, the phase shift will be $\eta_2 = N\pi/10$, where N is the number of d electrons.

Blandin [31] expressed the charge density oscillation of conduction electrons with spin σ around the impurity having a localized magnetic moment as

$$\Delta\rho^\sigma/r/ = -\frac{5}{4\pi^2} \sin \eta^\sigma{}_2 \; r^{-3} \cos(2k_F r + \eta^\sigma{}_2) \qquad /6/$$

where $\eta^\sigma{}_2$ stands for the phase shift of scattered electrons with spin σ. By making use of this expression the total electron charge density oscillation is given as

$$\Delta n/r/ = \Delta\rho^\uparrow/r/ + \Delta\rho^\uparrow/r/ \qquad /7/$$

and the spin density oscillation as

$$\Delta s/r/ = \Delta\rho^\uparrow/r/ - \Delta\rho^\uparrow/r/ \qquad /8/$$

on introducing the notation used by Souletie |32| the description can be simplified to

$$\begin{aligned} \eta^\uparrow 2 &= (1+\xi)\eta_2 \\ \eta^\downarrow 2 &= (1-\xi)\eta_2 \end{aligned} \qquad /9/$$

According to Souletie $\xi = 0$ corresponds to the "nonmagnetic" and $\xi = 1$ to the "magnetic" case. In the "nonmagnetic" case the Blandin-Souletie description corresponds to formula /4/ in the case of resonance scattering. In the magnetic case $\eta_2^\uparrow = 2\eta_2$ and $\eta_2^\downarrow = 0$ and the charge and spin density oscillations are equivalent, i.e.

$$\Delta n/r/ = \Delta s/r/ = -\frac{5}{4\pi^2} \sin 2\eta_2 r^{-3} \cos(2k_F r + 2\eta_2) \qquad /10/$$

In this simple model the charge density oscillation is brought about by the electrons polarized in spin. The amplitude of charge density oscillation in the "non-magnetic" case is proportional to $2\sin\eta_2$, in the "magnetic" case to $\sin 2\eta_2$, and the amplitude of spin density oscillation in the "magnetic" case is proportional to $\sin 2\eta_2$ and of course equal to zero in the case of $\xi = 0$.

In the case of localized moment it is easy to express in terms of the theory the hyperfine field due to spin density oscillation [31, 33] as

$$\Delta H/r/ = \frac{16\pi}{3} \mu_B \langle|\psi_{(o)}|^2\rangle \frac{\langle Sz\rangle}{s} \Delta s(r) \qquad /11/$$

where $\langle|\psi/O/|\rangle$ is the wave function of the electron with Fermi energy at the resonant nucleus in pure metal, μ_B is the Bohr magneton, $\langle S_z\rangle$ is the thermal average, S is the spin quantum number, H_o is the external field, k_B is the Boltzmann constant, T is the temperature and $\Delta s/r/$ is the spin density oscillation. $\Delta H/r/$ causes a H_o/T dependent broadening of the NMR spectrum.

$\langle|\psi(o)|^2\rangle$ can be determined if the Ruderman Kittel coupling constant is known |34, 35|. This formula reproduces the RKKY formula, except for the phase factor in $\Delta s/r/$, if the coupling constant J_{eff} is defined /for $\xi = 1$/ [3, 37] as

$$J_{eff} = (2\ell+1)\, J_{sd} = \frac{10\, E_F}{3\pi S} \sin 2\eta_2 \qquad /12/$$

The relations are utilized for the interpretation of the asymptotical values obtained from the measurement.

The preasymptotical form [34] of the charge density oscillation contains apart from the known Friedel oscillation a term in r^{-4}, that is

$$\Delta n/r/ = Ar^{-3} \cos(2k_F r + \;) + B\, r^{-4} \cos(2k_F r + \zeta) \qquad /13/$$

The definitions of B and ζ are given by formula /4/ in [38] in the form of sums representing the phase shifts and the derivatives of the phase shifts with respect to wave number, taken at k_F, respectively. According to the estimation of the authors B>A, thus the effect of r^{-4} is worth considering for close neighbours.

The above relations are those which will be utilized for the

interpretation of the experimental results. No numerical agreement is to be expected as the present theories and also those not referred to here neglect many possible contributions /the shape of the Fermi surface, the role of the d-electrons in Cu, etc./. It will be seen that the simple asymptotical theories give an understandable explanation of the phenomena far away from the impurities and that no quantitative description is available for those observed in the close environment of the impurities.

2. INTERPRETATION OF FIELD GRADIENT MEASUREMENTS

Prior to our review of the interpretation, we want to call attention once more to the problem concerning α. Each evaluation accepts the $\alpha = 25.5$ value, calculated by Kohn-Vosko [15], as a revelation, in spite of the fact, that no experimental verification is available and only an estimated upper limit is known [28]. Furthermore, nobody can be "a priori" sure, about characterizing the antishielding effect in the immediate vicinity of the impurity by a scalar quantity.

A s y m p t o t i c r e s u l t s. In spite of the fact, that in chronological order the work of Rowland [16] is the first one, we intend to start with the interpretation of the first order wipe-out number, for in this case, theoretically, an agreement of the asymptotic theory and the experimental results might be expected. The interpretations are discussed in the following groups: impurities with different valence, impurities with the same valence, 3d transition metal impuriuties, Ni, Pd, Pt impurities.

- Impurity with different valence. The evaluation was performed according to the /3/ and /4/ formulae and every phase shift system available in the literature was considered. The details of our evaluation and the above phase shifts are available in [7] and [19]. The measured wipe-out numbers were compared to those calculated according to the Langer-Vosko theory [39]. Within our evaluation, no other size effect than the Blatt-correction was considered. The results are shown in Fig.2. The following conclusions were drawn:

The experimental results are described by the Langer-Vosko theory only in case we are calculating with $\alpha = 18$ enhancement factor instead of $\alpha = 25.5$.

Regarding the phase shifts available in the literature the best agreement is obtained by using the Alfred-Van Ostenburg ones.

The first order wipe-out numbers calculated by the Kohn-Vosko phase shifts are by 60 per cent larger then the measured values.

Considering further measured quantities /impurity resistivity, Knight-shift measured on the melt/ we came to the conclusion, that the meas-

ured three quantities are not described properly by any of the known phase shift systems.

We tried [19] to get a graphical solution based on the Faber-Ziman diagram of the relation concerning the three physical quantities. The "empirical" phase shifts and the values of the n_1, impurity resistivity and of the Knight-shift, calculated by them, are summarized in Table IV. The results, shown in the Table, seem to prove the existence of a phaseshift system, by which the experimental results could be described. The elaboration of a "theoretical" phase shift system, by which the quantities measured experimentally could be more exactly described, would be an important step.

- The situation is even worse in case of Ag and Au impurities, if the evaluation was performed similarly to that performed in cases of Zn, Ga and Ge impurities [19], [7]. In this approach the Kohn-Vosko phase shift, giving the best agreement for the Ag impurity, describes well the Knight-shift measured on the melt, but gives a $\sim$ 60 per cent of the measured first order quadrupole wipe-out number. The n_1 is described well for Au impurity, but the Knight-shift is described with a wrong sign. We suppose, this is the case, where the neglecting of the size effect results the greatest error. The interpretation of the experimental data is not in the least sufficient.

- We might start the interpretation of the first order wipe-out numbers [20], [21], [7] measured on Cu based dilute alloys containing 3d transition metal impurities, according to the /3/, /6/ and /9/ relations. Presuming a dominant resonance scattering, we do not think, that the size effect is going to have an important part. In Fig. 3 the values of charge density oscillation amplitudes for a Cu-3d transition metal row and concerning the "non-magnetic" and "magnetic" limits are shown according to the simple model outlined in chapter II. The charge density oscillation amplitude scale and the measured wipe-out numbers were presented presuming "only resonance" scattering. /Considering the nonresonant scattering too, the two curves are getting asymmetric for the $Z_d = 5$ line; and on the right side of the Fig.3 the amplitude of n_2 and the n_1 are decreasing too/. Among the impurities the Mn and Fe are considered being in magnetic state and the Co and Ni being in non-magnetic state. No numerical agreement is expected, we are glad, that the most characteristic features of the measurement data are presented by the model. Similarly to cases of impurities with different valence, it was observed, that explicitly better agreements were obtained with a smaller α /in Fig. 3 $\alpha = 18$ is shown/.

The model is of a very interesting consequence: in $\xi = 1$ magnetic case from the $n_1 \sim \Delta n/r/ = \Delta s/r/$ /10 formula/ measurement, the $\Delta s/r/$ amplitude and the J_{eff} could be determined in case of a known S [37]. After the calculations were performed - presuming only resonant scattering - the following results were obtained for Cu-Mn, $J_{eff} = 1.6$ eV ($\alpha = 25.5$), $J_{eff} = 2.3$ eV

(α = 18) and presuming, that η_0 and η_1 were the same as those for N_i impurities [7] J_{eff} = 2.1 eV was obtained. For Cu-Fe and in all the three cases 3.2 eV, 4.5 eV and 3.8 eV were obtained.

- There is nothing more to say about the Cu-Pt, Cu-Pd and Cu-Ni rows, than that already discussed in [7]. The empirical phase shift system /η_0, η_1, η_2/ described there is acceptable from physical viewpoint, however, theoretically determined phase shifts are unknown.

P r e a s y m p t o t i c r e s u l t s. Interpreting the wipe-out numbers characteristic of the second order quadrupole effect, we are referring to the studies of Rowland [16] and Sagalyn et al [26]. We want to make some remarks on these studies and the problem itself. The n_1 wipe-out numbers are significantly overestimated in the asymptotic range by the Kohn-Vosko phase shifts used by them. Sagalyn et al [26] overestimated by a factor of 10 the λ parameter of the size effect [28]. Serfőző [40] obtained a good agreement on Cu-Zn, Cu-Ga and Cu-Ge alloys using the Alfred-Van Ostenburg preasymptotic formula /13/. In the same time the lattice deformation theory of Nagai [41] gave the n_2 = 33 wipe-out number [19] against the measured n_2 = 24. According to our opinion, the problem cannot be regarded for solved.

The interpretation of the field gradient measured at the place of the first and second neighbours was done by Jensen et al. [5] and Schnakenberg et al. [4]. These field gradients calculated by the Alfred-Van Ostenburg [38] self-consistent shielding potential and the Hurd-Gordon phase shifts and phase shift derivatives [42], are not sufficient, according to the unanimous opinion of authors. /In the model the field gradient has a cylindrical symmetry and so η = 0./ Similarly, the field gradient is not sufficient either when calculated by the Kohn-Vosko phase-shifts and the asymptotic formula /5/. We are of the same opinion as authors.

Considering the field gradient measured in the neighbours of the 3d transition metal impurities, no attempts were made for theoretical interpretations. Their low values, as compared to those of the other alloys, are remarkable anyway.

3. THE INTERPRETATION OF THE LOCAL MAGNETIC-FIELD MEASUREMENTS

The results of Table III cannot be interpreted by the /11/ relation or the RKKY formula, at the place of the first neighbours a positive shift is calculated in all the three cases [12], [17], [18] against the measured negative shift, however, the "disagreement" is not surprising at all [43]. Lo et al [17] were analyzing the results and came to the conclusion that in Cu-Ni and Cu-Co the quotient of the relative shift /$\Delta K_1/H_o$/ and $J_{sd}x$ /s-d coupling constant, impurity susceptibility/ is the same, as the consequence of the

simplest relation /11/. Their results and a similar analysis for Cu-Mn are presented in Table V. However, we have to admit, that the numerical agreement depends very much on the value of J_{sd} and in this field authors have an opportunity to choose from a wide variety.

IV. CONCLUSIONS

We do not intend to repeat our observations about the interpretation, we only want to emphasize some of the circumstances. It is obvious, that the key of development is the improvement of the theories of the problem. The research worker dealing with experiments, does not like to speak about an "agreement" with the theory, when the theoretical model is containing several negligances, the effect of which cannot be estimated. We have to mention the unanimous acceptance of the $\alpha = 25.5$ value, in spite of the fact, that Kohn and Vosko accepted the value of α for proper within the factor of 2 and in spite of the fact, that its experimental value is unknown. We intended to refer to this fact repeatedly in this paper, namely, that a smaller α offers better results. We wanted to show, that the solution of the α problem is of the same importance as the determination of the relation concerning the appropriate charge density or the lattice deformation. At last we want to establish, that presently - with the exception of the Cu-Ag and Cu-Au dilute alloys - the experimental results for the asymptotic range have the best interpretation.

AKNOWLEDGEMENT

Thanks are due to Prof.L.Pál and Dr.B.Vasvári for supporting this work, to my colleague Dr.Cs.Hargitai for valuable discussions.

TABLE I. Electric field gradient /in Å^{-3} units/ and asymmetry parameter for first and second nearest neighbours of impurities in copper

Alloy	First n.n. q_1	First n.n. η	Second n.n. q_2	Alloy	First n.n. q_1	First n.n. η	Second n.n. q_2
Cu-Zn[b]	0.75	0.27	0.04[c]	Cu-Ag[b]	0.22	0.75	0.18
Cu-Ge[a]	0.74	0.91	0.31	Cu-Au[b]	1.01	0.05	0.31
Cu-Cd[b]	0.58	0.04	0.16				
Cu-In[a]	0.84	0.32	0.31	Cu-Ni[d]	0.42	0.20	-
Cu-Sn[a]	0.88	0.64	0.44	Cu-Co[e]	0.19	0.57	-
Cu-Sb[a]	1.00	0.75	0.66	Cu-Mn[f]	$\leq$0.05	-	-

a: Jensen et al., ref [5]

b: Schnakenberg et al., ref [4]

c: Redfield, ref [11]

d: Lo et al., ref [17]

e: Lang et al., ref [12]

f: Tompa, ref [18]

TABLE II. Wipe-out numbers for the second /n_2/ and for the first /n_1/ order quadrupole effects in dilute Cu-based alloys

Alloy	n_2	n_1	Alloy	n_2	n_1
Cu-Zn	18[a] 17[b]	490±25[e]	Cu-Ag	25[a]	590±30[d]
Cu-Ga	38[a]	900±30[d]	Cu-Au	44[a] 44[b]	880±40[c]
Cu-Ge	63[a]	1400±50[d]	Cu-Mn		1500±75[e]
Cu-As	80[a]	-	Cu-Fe	-	2100±100[f]
Cu-Cd	32[a]	-	Cu-Co	-	2050 100[g]
Cu-In	48[a]	-	Cu-Ni	19[a,h] 24[b] 28[i]	1250±125[c]
Cu-Sn	67[a]	-	Cu-Pd	38[a,h] 33[b]	1200±100[c]
Cu-Sb	87[a]	-	Cu-Pt	60[a,h] 60[b]	1900±100[c]

a: Rowland ν_o = 4 MHz, ref [16]
b: Tompa ν_o = 6 MHz, ref. [7]
c: Tompa, ref. [7]
d: Serfőző et al., ref. [19]
e: Tompa, ref. [20]
f: Tompa et al., ref. [21]
g: Tompa, unpublished
h: Beal-Monod, ref. [22]
i: Chapman et al., ref. [24]

TABLE III. Local magnetic fields in some Cu-3d transition metal dilute alloys

Alloy	$\Delta K_1/H_o$	$\Delta K_2/H_o$	$\Delta K_3/H_o$	Temp. ^oK
Cu-Mn[a]	-4.87 0.2		-	300
Cu-Co[b]	-3.84 0.04	1.91 0.02	-0.72	4.2
Cu-Ni[c]	-0.27 0.03	-	-	4.2

a: Tompa, ref. [18]

b: Lang et al., ref. [12]

c: Lo et al., ref. [17]

TABLE IV. Empirical phase shifts, first order wipe-out number, impurity resistivity and Knight shift /in smelts/ calculated on the basis of Faber-Ziman diagrams

Alloys	Phase shifts			n_1		$\Delta\rho$ / μ ohmcm/at%		$-\frac{1}{k}\cdot\frac{\partial k}{\partial c}$	
	η_0	η_1	η_2	measured	calc.	measured	calc.	measured	calc.
Cu-Zn	0.22	0.24	0.05	490	400	0.33	0.33	0.19	0.25
Cu-Ga	0.52	0.57	0.15	900	820	1.42	1.50	0.60	0.49
Cu-Ge	0.71	0.90	0.15	1400	1800	3.75	3.905	1.07	0.90

TABLE V. To the interpretation of local magnetic fields in some Cu-3d transition metal dilute alloys

Alloy	Cu-Mn[c]	Cu-Co[d]	Cu-Ni[d]
a: $\frac{K_1}{H_o}$	$-4.87.10^{-3}$	$-3.84.10^{-3}$	$-0.24.10^{-3}$
b: $/\frac{emu}{at}/$	16.10^{-27}	$4.0.10^{-27}$	$0.24.10^{-27}$
$\lvert\frac{a}{b}\rvert$ $/10^{24}/\frac{emu}{at}/^{-1}/$	0.30	0.96	1.0
$\lvert J_{sd}\rvert$ /eV/	0.32 0.42	0.19	1.35
$\lvert\frac{a}{J_{sd}.b}\rvert$	0.94 0.71	0.80	0.74

c: room temp. values, and $J_{sd} = J_{eff}/\ /2\ 1+1/$ from our mentioned results J_{eff} = 1,6 eV and J_{eff} = 2,1 eV respectively.

d: Lo et al., ref. [17]

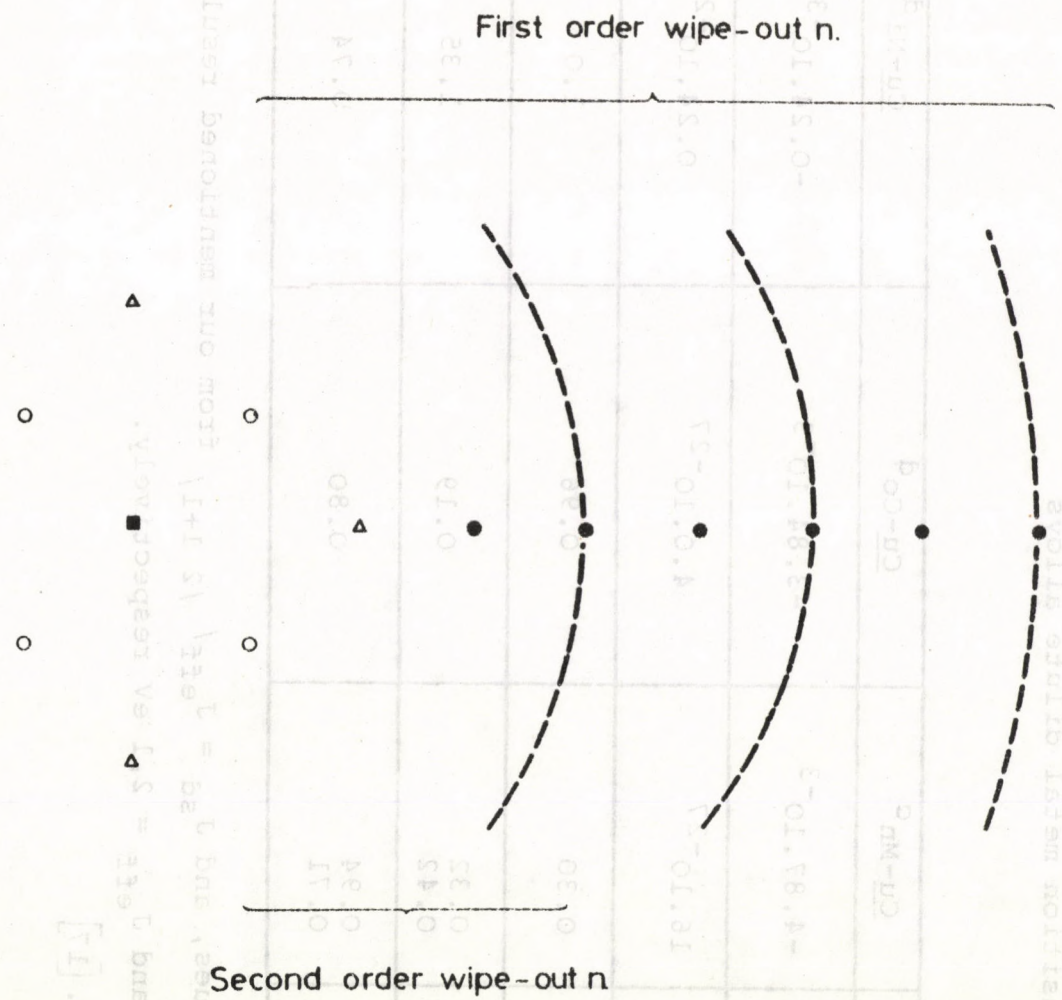


Fig.1 To the separation of field gradient measurements

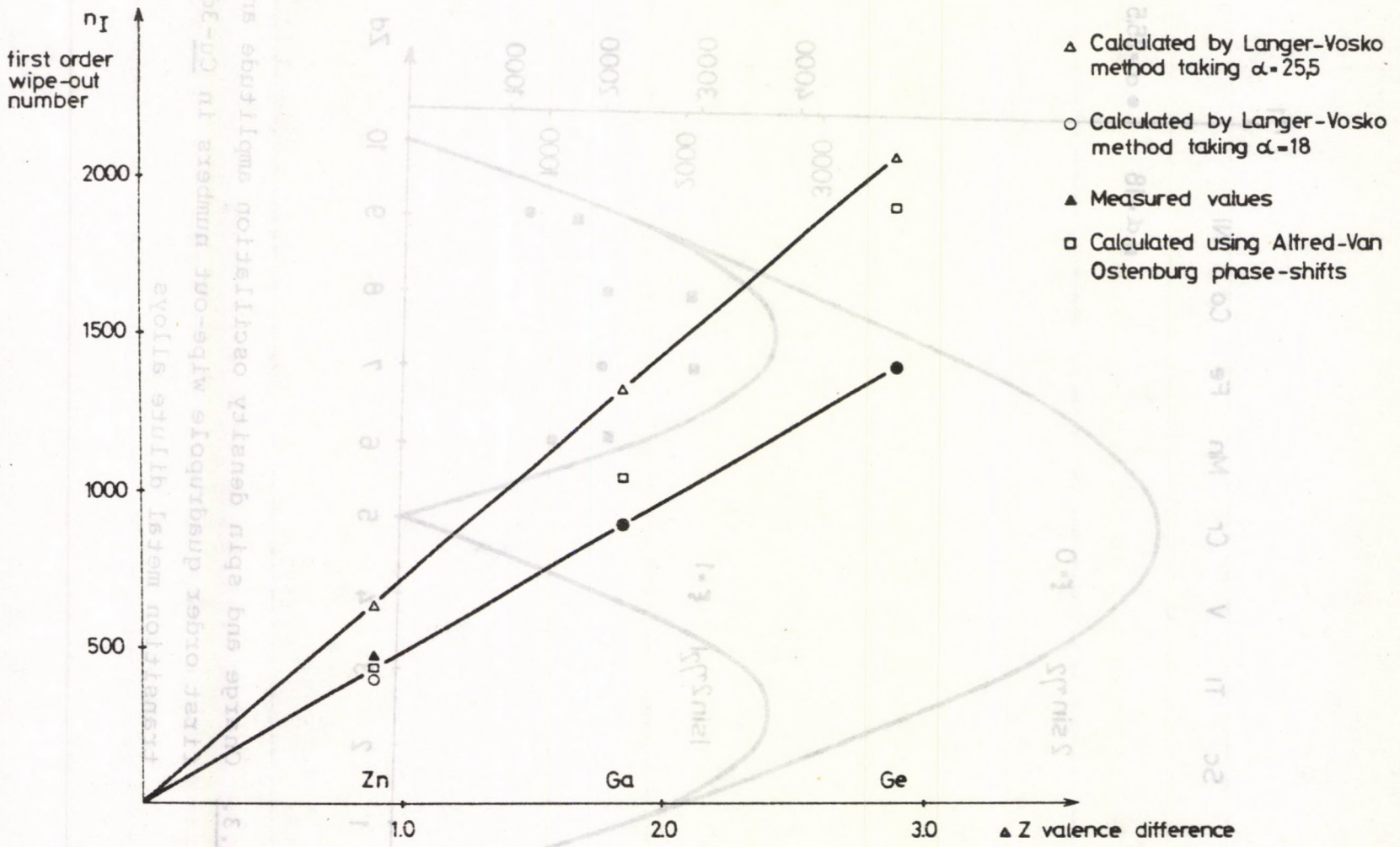


Fig.2 First order quadrupole effect in Cu-Zn, Cu-Ga, Cu-Ge dilute alloys

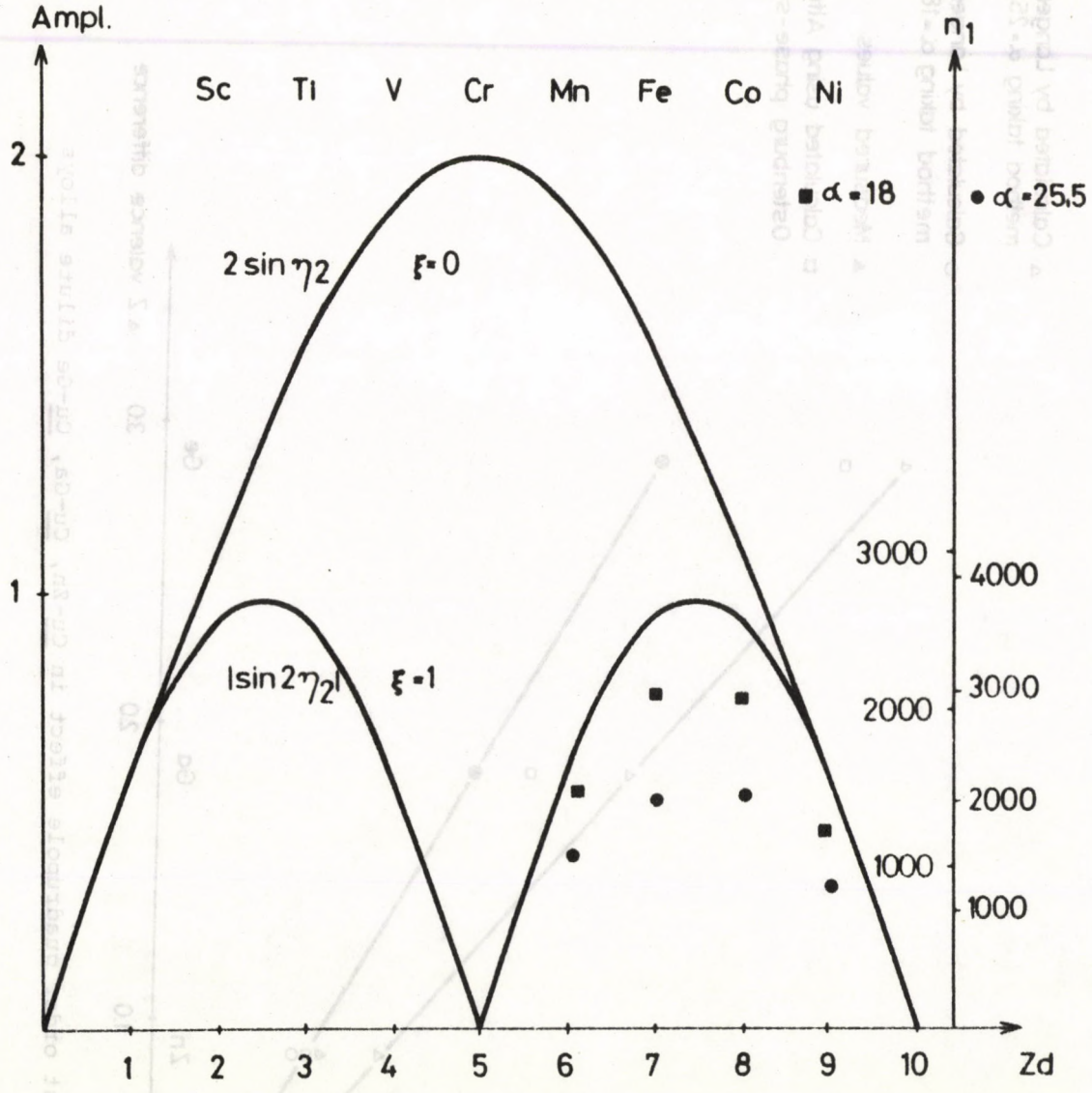


Fig.3. Charge and spin density oscillation amplitude and first order quadrupole wipe-out numbers in Cu-3d transition metal dilute alloys

REFERENCES

[1] J.Kondo, Solid State Physics 23, 184 /1969/

[2] A.J.Heeger, Solid State Physics 23, 283 /1969/

[3] A.Narath, Crit.Rev. Solid State Sci. 3, 1 /1972/

[4] R.T.Schumacher, G.Schnakenberg, Solid State Comm. 7, 1735 /1969/
G.Schnakenberg, R.T.Schumacher, Phys.Rev.B. 7, 2292 /1973/

[5] B.L.Jensen, R.Nevald, D.L.Williams, J.Phys.F. 2, 169 /1972/

[6] K.Tompa, F.Tóth, Physica Status Solidi 3, 2051 /1963/

[7] K.Tompa, J.Phys.Chem.Solids 33, 163 /1972/

[8] M.A.Adawi, KFKI-preprint, to be published

[9] A.Lovas, G.Serfőző, J.Tóth, K.Tompa, KFKI-preprint to be published

[10] D.Howling, Phys.Rev. 155, 642 /1967/

[11] A.Redfield, Phys.Rev.130, 589 /1963/

[12] D.V.Lang, J.B.Boyce, D.C.Lo, C.P.Slichter, Phys.Rev.Letters 29, 776 /1972/

[13] A.Abragam, The Principles of Nuclear Magnetism, Clarendon Press, Oxford /1961/

[14] J.Friedel, Phil.Mag. 43, 153 /1952/
A.Blandin, J.Friedel, J.Phys.Radium 21, 689 /1960/

[15] W.Kohn, S.H. Vosko, Phys.Rev. 119, 912 /1960/

[16] T.J.Rowland, Phys.Rev. 119, 900 /1960/
T.J.Rowland, N.Shiotani, A.I.M.E. Conference, 1965.

[17] D.C.Lo, D.V.Lang, J.B. Boyce, C.P.Slichter, Phys.Rev.B. 8, 973 /1973/

[18] K.Tompa, KFKI-preprint, to be published in Phys. Status Solidi

[19] G.Serfőző, K.Tompa, A.Lovas, KFKI-preprint, to be published

[20] K.Tompa, Proc.Low.Temp.Phys.LT-12 Kyoto 1970. KFKI preprint 70-31 SSP

[21] K.Tompa, A.Lovas, L.Zámbó, Phys.Status Solidi /b/ 54, K17 /1972/

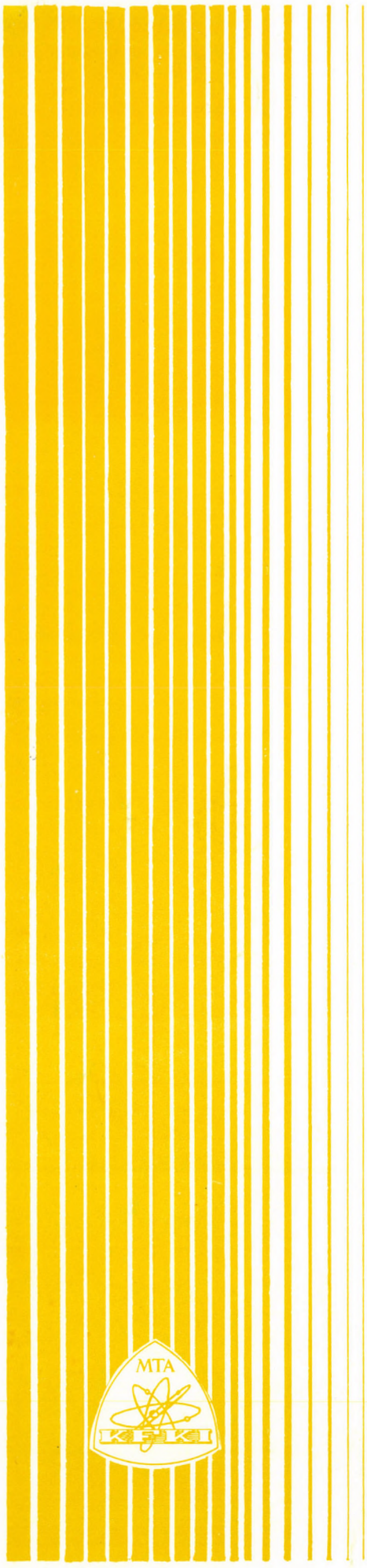
[22] M.Beal-Monod, Phys.Rev. 164, 360 /1967/

[23] J.Owen, M.E.Browne, W.D.Knight, C.Kittel, Phys. Rev. 102, 1501 /1956/
J.Owen, M.E.Browne, V.Arp, A.F.Kip, J.Phys.Chem.Solids 2, 85 /1957/

[24] R.E.Behringer, J.Phys.Chem.Solids 2, 209 /1957/ W.Van der Lugt, N.J. Poulis, W.P.A.Hass, Physica 25, 97 /1959/
A.C.Chapman, E.W.F.Seymour, Proc.Phys.Soc. 72, 747 /1959/
T.Sugawara, J.Phys.Soc.Japan, 14, 643 /1959/

[25] D.C.Golibersuch, A.J.Heeger, Phys.Rev. 182, 584 /1969/

[26] P.L.Sagalyn, A.Paskin, R.Harrison, Phys.Rev. 124, 428 /1961/
[27] F.J.Blatt, Phys.Rev. 108, 285 /1967/
[28] K.Tompa, F.Tóth, E.Nagy, Phys.Status Solidi 41, 413 /1970/
[29] R.M.Steinheimer, M.M.Foley, Phys.Rev. 102, 731 /1956/
[30] J.M.Brettell, A.J.Heeger, Phys.Rev. 153, 319 /1967/
[31] A.Blandin, J.Appl.Phys. 39, 1285 /1964/
[32] J.Souletie, J.Low Temp.Phys. 7, 141 /1972/
[33] A.Blandin, Varenna Lecture Notes /1966/
[34] K.Tompa, Phys.Status Solidi 18, 391 /1966/
[35] E.R.Andrew, Magnetic Resonance and Related Phenomena, ed.V.Hovi, North Holland - Elsevir 1973. p:18
[36] Y.Yoshida, Phys.Rev. 106, 893 /1957/
[37] K.Tompa, KFKI preprint 73-31
[38] L.C.R.Alfred, D.O.Van Ostenburg, Phys.Letters 26A, 27 /1969/
[39] J.S.Langer, S.H.Vosko, J.Phys.Chem.Solids 12, 196 /1969/
[40] G.Serfőző, KFKI-preprint, to be published
[41] O.Nagai, J.Phys.Soc.Japan 20, 509 /1965/
[42] C.M.Hurd, E.M.Gordon, J.PHys.Chem.Solids 29, 2205 /1968/
[43] D.J.W. Geldart, Phys.Letters A. 38, 25 /1972/



Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Vasvári Béla igazgatóhelyettes
Szakmai lektor: Hargitai Csaba
Nyelvi lektor: Almási Katalin
Példányszám: 290 Törzsszám: 74-9629
Készült a KFKI sokszorosító üzemében, Budapest,
1974. február hó